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DUAL LOOP COMPENSATOR FOR EFFICIENT QUADRATIC BOOST CONVERTER

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ABSTRACT

To overcome the disadvantages of higher duty ratio of normal boost converter a quadratic boost converter is proposed. This has been generalised to the n^{th} order boost converter. The dynamic performance of the quadratic boost converter for the changes in the input voltage, reference voltage and the load is simulated. The output voltage is traced to the desired value with the help of the closed loop controlled compensator for the perturbations caused in the input, load and reference voltages. The compensation includes a multi loop control with inner current loop and an outer voltage loop control. The inner current loop provides the benefits of setting the reference voltage and outer voltage loop provides a good regulation of the output voltage. A design oriented analog circuit of the closed loop controller is produced with simulation results.

KEYWORDS: Multiloop Control, Voltage Mode Control, Current Mode Control

INTRODUCTION

DC-DC conversions are found to have major applications in industry, organisations, and in day-to-day life with the change in the technology [1]. Sometimes the application needs an amplified voltage on the output, for which the boost topology can be utilised. A still further increase in the voltage is forecasted as a part of the revolution in technology. To increase the output voltage on the output the duty ratio has to be increased, which makes us compromise on the efficiency of the converter. When the duty ratio is operating at its maximum limit it becomes difficult to compensate the changes in the load and as well as the changes in the reference and input voltages [2]. To serve the purpose of increased voltage a cascaded boost converter can be utilised. This converter topology can increase the voltage than the basic boost topology for a given duty ratio. The major disadvantage of this converter is the degradation of the efficiency because of the increased switching losses. If the voltage conversion ratio has to be quadratically dependent on the duty ratio then the best solution would be the usage of quadratic converter. Maksimovic and cuk had stated different quadratic converter topologies and their operations [3]. The quadratic converter topology provides an electrical equivalence as the cascaded converter but uses only a single switch.

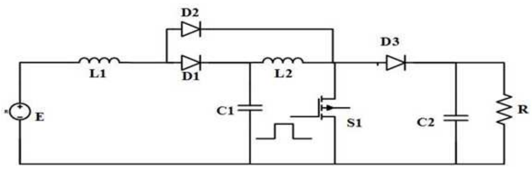

Figure 1: Quadratic Boost Converter

The two LC filters incorporated in the converter is the reason for the fourth order dynamics exhibited by the converter. Applying the volt-sec balance across the two inductors the voltage conversion ratio of this converter is given by

$$M = (\frac{V_O}{V_g}) = (\frac{1}{1-d})^2$$

The voltage stress on the active switch and on the diode which is on the output side is equal to output voltage. This stress can be reduced by incorporating the energy storage elements as discussed by [7].

The practical values of the on-state resistance drop of switch R_{NMOS}, the drain to source capacitance value C_{DS} the effective resistance of inductor R_L the forward cut in voltage of the diode V_F are utilized to calculate the efficiencies of the cascaded boost and quadratic boost converter. The presence of the extra switch which is present in the cascaded boost converter decreases the efficiency than that of the quadratic boost converter.

$$P_{IN} = P_{SWITCH} + P_{DIODE} + P_{INDUCTOR} + P_{OUT}$$

$$\text{Efficiency of the converter} = \frac{P_{IN} - (P_{SWITCH} + P_{INDUCTOR} + P_{DIODE})}{P_{IN}}$$

Where

$$P_{SWITCH} = R_{NMOS} * D * \left(\frac{I_{OUT}}{(1-D)^2}\right)^2 + \frac{1}{2} * C_{DS} * V_{OUT}{}^2 * f_{SW} + \frac{1}{2} * C_D * V_{OUT}{}^2 * f_{SW}$$

$$P_{INDUCTOR} = R_L * \left(\frac{I_{OUT}}{(1-D)^2}\right)^2$$

$$P_{DIODE} = R_D * I_{OUT}{}^2 + V_F * I_{OUT}$$

The calculated efficiency obtained for the cascaded boost is 82.89% and whereas for the quadratic boost converter it is 86.9% this is the reason why a quadratic boost converter is preferred over the cascaded boost converter. This is one of the major advantages when we use a single switch quadratic boost converter over a cascaded boost converter.

When the energy storage elements i.e., LC filters are increased with utilization of a single switch, a quadratic boost converter is formulated. This quadratic boost converter is electrically equivalent to that of the cascaded boost converter but has a higher efficiency as mentioned in the earlier section. This quadratic nature of the voltage conversion ratio can be extended to a cubic dependence of the duty ratio by increasing the energy storage elements. This cubic dependence of the voltage conversion ratio on the duty ratio utilizing a single switch is electrically equivalent to a three stage cascaded boost converter. This converter exhibits sixth order dynamics. The three stage boost converter using a single switch is as shown

in the figure below. The voltage

Conversion ratio is given by

$$M = \left(\frac{V_0}{V_g}\right) = \left(\frac{1}{1-d}\right)^3$$

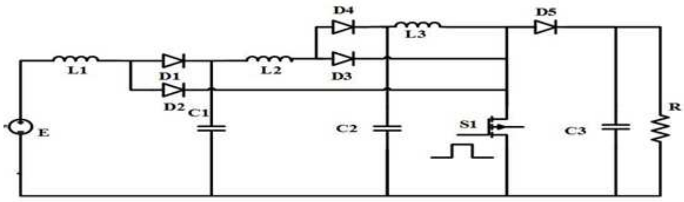

Figure 2: Three Stage Boost Converter

This quadratic dependence of the duty ratio can be extended to nth order dependence by increasing the stages of energy storage elements to n number of order [4]-[6]. The voltage conversion ratio can be given by

$$M = \left(\frac{V_0}{V_g}\right) = \left(\frac{1}{1-d}\right)^n$$

Where n is the number of stages

This paper provides the dynamic response of the system for the changes in the input voltage, reference voltage and switching of load. Basically current mode control and the voltage mode control are available for the closed loop control of a system[8]. This modes of control helps to reduce the influence of the disturbances occurred due to input, reference voltages and changes in load on the output voltage. In the voltage mode control, the output voltage is considered for the feedback purpose. In the current mode control the first inductor current of the quadratic boost converter has to be utilised. The second inductor current has a non-minimum phase transfer function this is the reason why we utilise only the first inductor current for feedback control. The purpose of this paper is to provide a multi loop control of the quadratic boost converter. For the control model the transfer functions of the output voltage and inductor current to that of the control signal are obtained through linearization techniques.

This paper is presented with linearization of the proposed quadratic boost converter as shown in section II. A multi loop control with current mode and voltage mode controller is presented in section III . A design analysis of the compensated converter is presented in section IV. The simulated results of the dynamic response with changes in input, reference voltages and changes in load is presented as a part of section V.

II. LINEARISATION OF THE CONVERTER

The converter changes back and forth between the two switching states. To represent the control model these switching states are to be dynamically represented through averaging. The state space representation of the on-state and off-state is utilised for the averaging model.

$$\dot{x}_{avg} = Ax + BV_g = \left(A_1 d + A_2(1-d)\right)x + (B_1 d + B_2(1-d)V_g)$$

$$y = Cx = \left(C_1 d + C_2(1-d)\right)x$$

In the above equations the matrices A,B,C are valid functions of the duty ratio of the quadratic converter. In order to define different transfer functions for the controlling we need to linearise the equations. To obtain the dynamic response of the system we consider the perturbations in the dynamic variables which can be obtained as time varying inputs in d(control signal) and V_g(input voltage)

$$\dot{X} + \hat{\dot{x}} = \left(A_1 d + A_2(1-d)\right)(X + \hat{x}) + \left(B_1 d + B_2(1-d)\right)(V_g + \widehat{V_g})$$

$$V_0 + \widehat{v_0} = \left(C_1 d + C_2(1-d)\right)(X + \hat{x})$$

The dc term, linear and nonlinear small signal terms are obtained from the above equations as given below:

$$0 = Ax + BV_g \ldots\ldots\ldots \text{dc term}$$

$$\hat{\dot{x}} = A\hat{x} + B\widehat{V_g} + \left((A_1 - A_2)\right)x + (B_1 - B_2)V_g)\hat{d} \ldots\ldots \text{linear model}$$

The transfer functions are obtained by using

$$X = A^{-1}BV_g$$

$$\hat{\dot{x}} = A\hat{x} + B\widehat{V_g} + f\hat{d}$$

Where

$$f = [(A_1 - A_2)X + (B_1 - B_2)V_g]$$

The transfer function of output voltage to that of control signal is given by

$$\frac{\widehat{V_o}}{\hat{d}} = \frac{S^3 a_0 + S^2 a_1 + Sa_2 + a_3}{S^4 + S^2 b_0 + b_1} \ldots\ldots\ldots(a)$$

Where

$$a_0 = \frac{1}{C_2 R g^3}$$

$$a_1 = \frac{-1}{L_2 C_2 g}$$

$$a_2 = \frac{2}{L_2 C_1 C_2 R g^3} + \frac{2}{L_1 C_1 C_2 R g}$$

$$a_4 = -2Rg^5$$

$$b_0 = \frac{g^2}{L_1C_1} + \frac{1}{L_2C_1} + \frac{g^2}{L_2C_2}$$

$$b_1 = \frac{g^4}{L_1L_2C_1C_2}$$

The transfer function of inductor current to that of control signal is given by

$$\frac{\widehat{i_{L1}}}{\hat{d}} = \frac{S^3a_0 + S^2a_1 + Sa_2 + a_3}{S^4 + S^3b_0 + S^2b_1 + Sb_2 + b_3} \dots\dots (b)$$

where

$$a_0 = \frac{-1}{C_1g}$$

$$a_1 = \frac{-1}{L_1C_2Rg},$$

$$a_2 = -\left(\frac{g}{L_2L_1C_2} + \frac{2}{L_1C_1L_2g}\right)$$

$$a_3 = \left(\frac{-3Rg^2 + 1}{L_1L_2C_1C_2R^2g^3}\right)$$

$$b_0 = \frac{1}{C_2R},$$

$$b_1 = \frac{L_1C_1g^2 + L_1C_2 + L_2C_2g^2}{L_1L_2C_1C_2}$$

$$b_2 = \left(\frac{L_1 + L_2g^2}{L_1L_2C_1C_2}\right)$$

$$b_3 = \frac{Rg^3}{L_1L_2C_1C_2}$$

Here g = (1-d)

III. MULTI LOOP CONTROL

The fundamental idea behind the closed loop control of quadratic boost converter is by sensing the output voltage

and inductor current. The output voltage information obtained using voltage sensor is fed back and compared with a reference voltage. The error obtained through this comparison is fed through the voltage loop feedback compensator. The inductor current is sensed and fed back, practically this can be obtained with the help of a resistor. This overall gain utilized is termed as the inductor current sensing gain[9].This is fed to the circuit with the help of a current loop feedback compensator and is compared with that of the output of voltage loop feedback compensator. The obtained output is utilized for the generation of the pulses after comparing it with the reference voltage. The peak amplitude of the triangular reference voltage has a prime importance for the generation of required pulses.

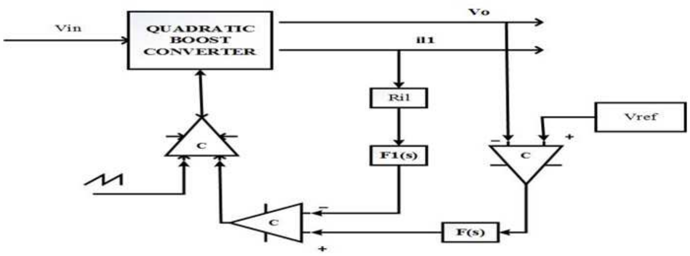

Figure 3: Multi Loop Compensation of Quadratic Boost

The basic block for this multi loop control is represented in Fig.4. Here (I), (II),(III) represents the input, load and reference voltages respectively. To obtain the dynamic response the part (I) is replaced by the Fig.5(a) This shows the change in the input voltage. The part (II) of the figure is replaced by the change in the load as shown in Fig.5(b) Whenever there is a change in the reference voltage the (III) part of the Fig.4 is replaced by Fig.5(c).

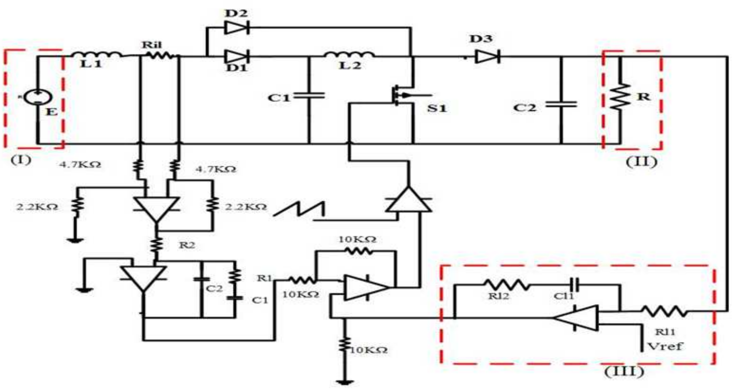

Figure 4: Multi Loop Control of Quadratic Boost Converter for Changes in Input Voltage, Changes in Load and Changes in Output Voltage

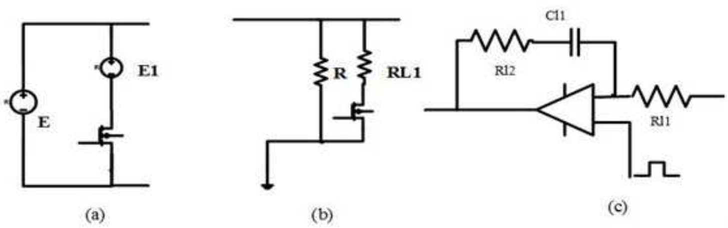

Figure 5: (A) Step Change in Input Voltage (B) Change in the Load (C) Step Change in Reference

So, whenever there is a change in the reference voltage the error obtained after the comparison of the reference

voltage with that of output voltage is fed through the compensator and accordingly the duty ratio of the converter changes and this allows the output voltage follow the reference voltage. Not only the changes in the reference voltage but also the sudden changes in the input and also the load will be traced and the error generated will change the duty ratio in order to obtain the required output voltage.

IV.DESIGN OF CONTROLLER

The two transfer functions (a) and (b) are used to the design the compensator. The transfer function of the output voltage and inductor current to that of the control signal have inherent oscillation phenomenon.

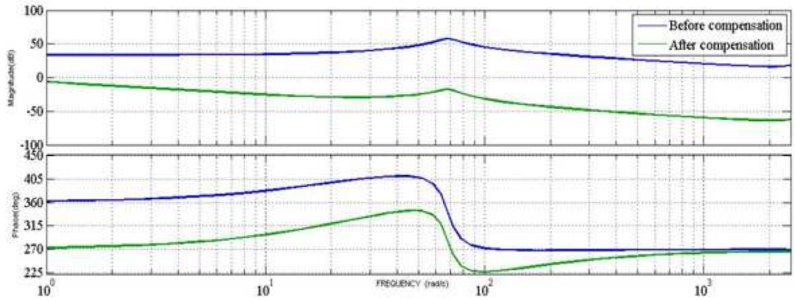

Figure 6: Bode Plot of Current Loop

The Bode plot as shown in Fig.6 of the transfer characteristics shows a peak because of the inherent oscillations present and this function is utilized to design a compensator. In order to reduce the peak oscillations a lag compensator is chosen. This compensator has a form of

$$F(S) = A\frac{\left(1+\frac{S}{\omega_1}\right)}{\left(1+\frac{S}{\omega_2}\right)}(\omega_1 > \omega_2)$$

is utilized for the voltage loop and an integrator with lag compensator of the form

$$F_1(S) = A\frac{\omega_0}{s}\frac{(1+\frac{S}{\omega 1})}{(1+\frac{S}{\omega 2})}$$

is incorporated into the current loop. The inner current loop is firstly designed with integrator with lag compensator and later a lag compensator is developed for the outer voltage loop.[a].In order to get a steady state error of 2% the gain of the compensator has been designed accordingly. A value for the inductor current sensing gain is chosen according to the bode plot.[b].The oscillation peak in the bode plot gets reduced with the designed compensators.[c].The gain at low frequencies has been chosen high in order to improve the steady state accuracy.

V. SIMULATION RESULTS

The above circuit as shown in Fig.4 and Fig.5 are simulated using the MATLAB SIMULINK and the results are plotted as shown below. The fig.7. and fig.8. Shows the change in the output voltage and current for the changes in the input voltage. The fig.9. and fig.10 indicates the changes in the output voltage and current for the changes in the load before and after compensation. The fig.11 and fig.12 represents the compensated output voltage and current for the change

in the reference voltage.

The values used for the simulation are

Table 1: Values Used for Simulation of Analog Circuit

Variable	Value
R1	250ohm
C1	10uF
R2	500ohm
C2	10uF
Rl1	270ohm
Cl1	10nF
Rl2	1000ohm

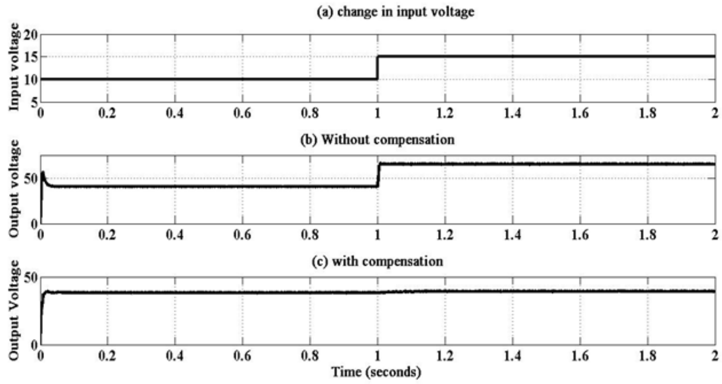

Figure 7: Change in Output Voltage for Change in Input Voltage

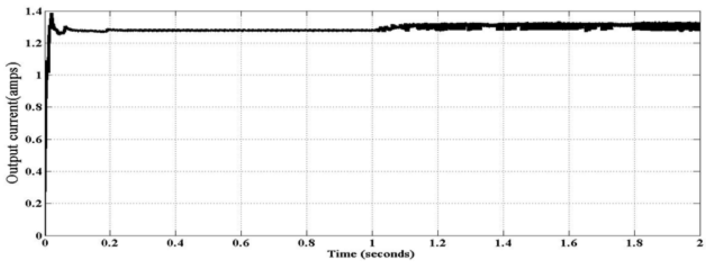

Figure 8: Change in Output Current for Change in Input Voltage

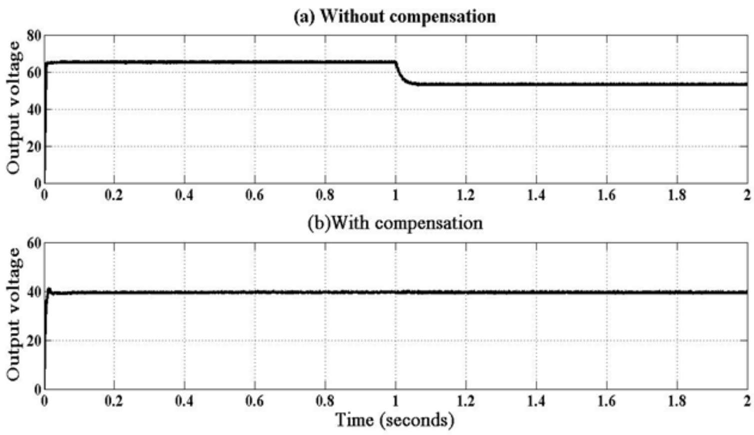

Figure 9: Output Voltage for Change in the Load

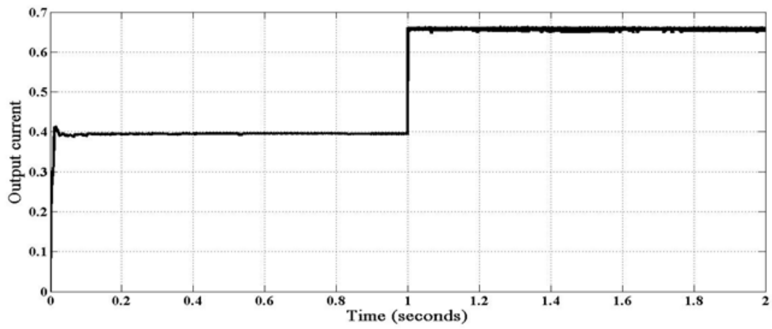

Figure 10: Output Current for Change in Load

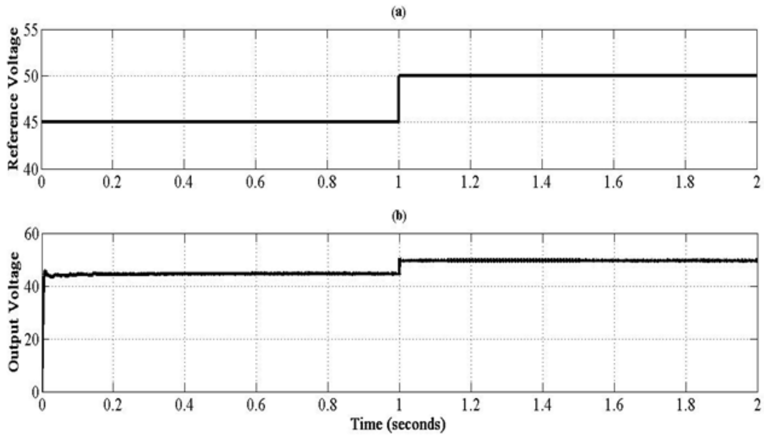

Figure 11: Change in Output Voltage for Change in Reference Voltage

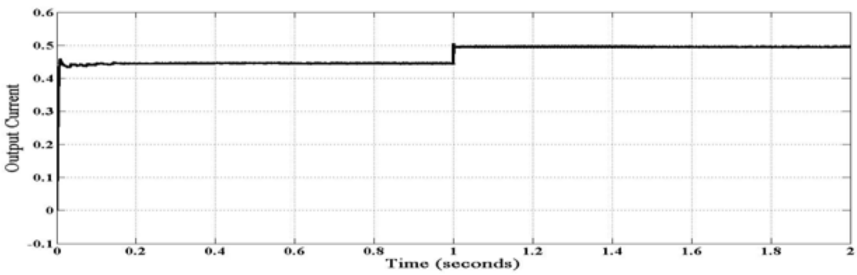

Figure 12: Change in Output Current for Change in Reference Voltage

CONCLUSIONS

The usage of single switch unlike the cascaded boost converter adds a major advantage to the quadratic boost converter. The two LC filters incorporated in the converter are the reason for forth order dynamic behaviour. The response of the converter for the changes in the input, reference voltages and load can be controlled by the closed loop compensator design. The inner current loop adds an advantage in protecting the circuit for over currents, and the outer voltage loop helps in maintaining the regulation of the converter. The control of the steady state error with proper design of the compensator is also presented.

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